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# A STUDY OF THE DAMAGE TO BRIDGES DURING EARTHQUAKES.[1]

### WM. HERBERT HOBBS

To the study of the damage sustained by buildings during earthquakes a vast amount of attention has been devoted, while other structures, better suited to reveal the nature of the disturbance have hardly been examined at all from the scientific standpoint. This is in part to be explained because the damage has been supposed to result wholly from elastic waves, but in part it has been determined by the obvious necessity of safeguarding the lives of the inmates of the buildings. Adopting the newer viewpoint that the vibrations felt at the surface of the earth are genetically at least a secondary rather than a primary cause of the disturbance, our attention must be turned in a different direction. In place of high structures we must study low ones, and from inspecting damage at isolated points we must note the distribution of the damage along complete sections crossing the affected district. Buildings thus give place in importance to railways, pipe lines, and to metal cables, and in fact to any *continuous* structures of fairly uniform strength and rigidity over long distances. Such structures are suited to register either tensional or compressional stresses.

Railway tracks, now the most generally available of these structures, preserve a record of tension in the tearing out of fish-plates and separation of rail ends, and of compression in the jamming of the joints and the buckling or kinking of the metals. The first and most striking result of observation of the damage to such structures, is the common occurrence of distinctly local maxima of deformation (see Fig. 1, *C* and *D*). The zones of deformation are not always, however, so narrow as in these instances, but may be betrayed by a sinuous course of the rails extending over a considerable fraction of a mile (see Fig. 1, *A*).

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[1] A paper read before the American Association for the Advancement of Science at the Chicago Meeting, December, 1907.

There is a type of structure whose sensitiveness for recording earth movements seems never to have been given its due weight, for we look in vain for any grouping of the evidence from damage sustained by bridges at the time of earthquakes. The writer has recently noted in a brief statement the rather common observation that the abut-

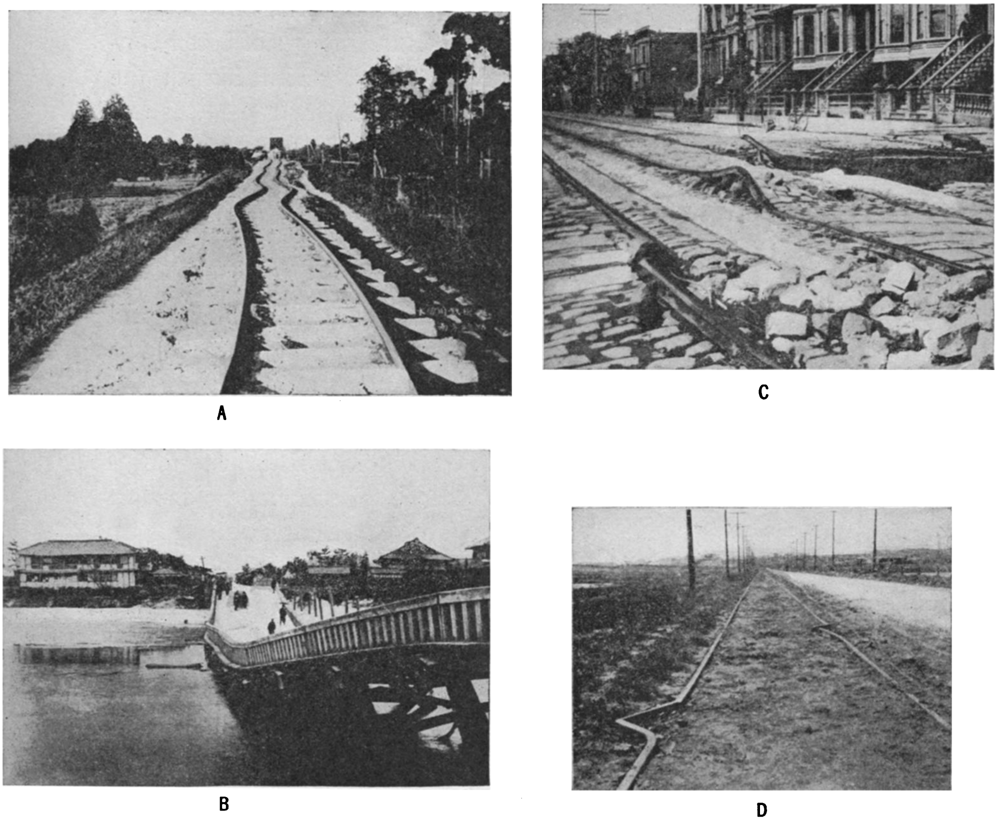

FIG. 1.—(*A*) Compressed railway tracks in the approach to the Kisogawa Railway bridge after the Japanese earthquake of 1891 (after Milne and Burton). (*B*) Biwajima Road bridge thrown into a serpentine form during the Japanese earthquake of 1891 (after Milne and Burton). (*C*) Car tracks which have sustained a sharp local compression along an oblique intersecting line. California earthquake of 1906 (after H. W. Fairbanks). (*D*) Electric railway tracks near San Francisco, showing a sharp local compression along an oblique intersecting line. California earthquake of 1906 (after Moran).

ments of bridges have approached each other during earthquakes,[1] and it is now proposed to assemble the evidence on which the statement was based and to suggest an explanation of the phenomenon. It is to the descriptions of destructive earthquakes of comparatively recent date and in countries of considerable industrial development that we must go for our evidence, since it is the bridges of better construction, and the railroad bridges especially, which furnish the most satisfactory evidence. Data are available from the Charleston earthquake of 1886, the Japanese earthquakes of 1891 and 1894, the Indian earthquake of 1897, the California earthquake of 1906, the Kingston earthquake of 1907, and probably others.

### THE "CHARLESTON" EARTHQUAKE OF AUGUST 31, 1886

A typical illustration is here furnished by the Charleston and Savannah Railway bridge over the Ashley River after the earthquake of August 31, 1886.[2] The diagrammatic sketch after Dutton, which is reproduced here in Fig. 2, is especially valuable, since it well illustrates a characteristic distortion of the abutments of bridges observed after a destructive earthquake. Of this bridge Dutton says:

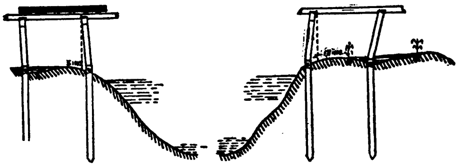

FIG. 2.—Bridge over the Ashley River, South Carolina, as it appeared after the earthquake of August 31, 1886 (after Dutton).

> The approach to the bridge is by a long embankment, traversing a marshy flat with an ascending grade, giving place near the bridge to a high trestle. An embankment and trestle lead to the bridge from the opposite side. The draw-bridge was closely jammed by the earthquake, the immediate cause being the sliding or creeping of both river banks toward the center of the stream, carrying the trestle with them. West of the river the joints of the rails were torn open by tension produced in this sliding motion. (P. 304.)

The only other railroad bridge within the so-called "epicentral tract" of this earthquake was on the same line of railway near Rantowles Station:

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[1] *Earthquakes, An Introduction to Seismic Geology* (D. Appleton & Co.), 1907, p. 230.

[2] C. E. Dutton, "The Charleston Earthquake," *9th Annual Report*, U. S. Geol. Survey, p. 231.

> The piling, which affords no indication of relative movement from inclosing earth, has dragged attached bents from vertical positions and jerked the superstructure from opposite sides to the center line with violence, wrecking rails, bulging up stringers, forcing up the caps of bents which were mortised with four-inch tenons, and in general affording liberal indications of shortening of the distance separating banks. (Pp. 304, 305.)

Of culverts and trestles there were many which received serious damage at the time of this earthquake, and all appear to have been deformed by a longitudinal compression.[1]

### THE MINO-OWARI EARTHQUAKE OF OCTOBER 28, 1891[2]

This earthquake has furnished some of the best illustrations anywhere available of the nature of damage to bridges during a destructive earthquake.

> The Biwajima-Bashi, a wide wooden carriage bridge across the Schonaigawa, was completely wrecked. It lies in the bed of the river in a curious serpent-like twisted form. The river is very low, and the continuity of the bridge was nowhere actually broken, so it was possible to walk across, though the feat was not an easy one on account of the angle at which the footway was canted. (See Fig. 1, *B*.)
>
> A brick railway bridge near the Biwajima River presented a singular appearance. The abutments which ordinarily had been perpendicular, had apparently been pushed backward to the right and left, and the arch which they ordinarily supported lay in two huge quadrant shaped masses blocking up the roadway between them. (See Fig. 3, *D*.)

Speaking of the Kisogawa bridge, Milne and Burton say:

> *a*) *Approaches.*—A more important feature is, however, the serpent-like bending of the line. Not only have the metals been deflected, but the embankment has suffered a parallel deformation. It seems as if the country here—and similar appearances are presented at other places—had been subjected to a permanent longitudinal compression. At each of these bends, although not shown in the present picture, to the right and left of the line, there is generally a slight compression in the general contour of the country which possibly may mark the line of an ancient watercourse, in which we may imagine that the materials are softer than elsewhere. (See Fig. 1, *A*.)
>
> *b*) *Bridge.*—The lateral shifting of the foundations by which the distances between the piers have been reduced, has been the result of a permanent compression which, had the bridge been represented by a line across the river bed, would have been contorted into one or more snake-like bends. (See Fig. 3, *A*.)

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[1] *Loc. cit.*, pp. 286, 290.

[2] John Milne and W. K. Burton, *The Great Earthquake in Japan*, 1891, Yokohama, (Lane, Crawford & Co., 1892), 2d ed.

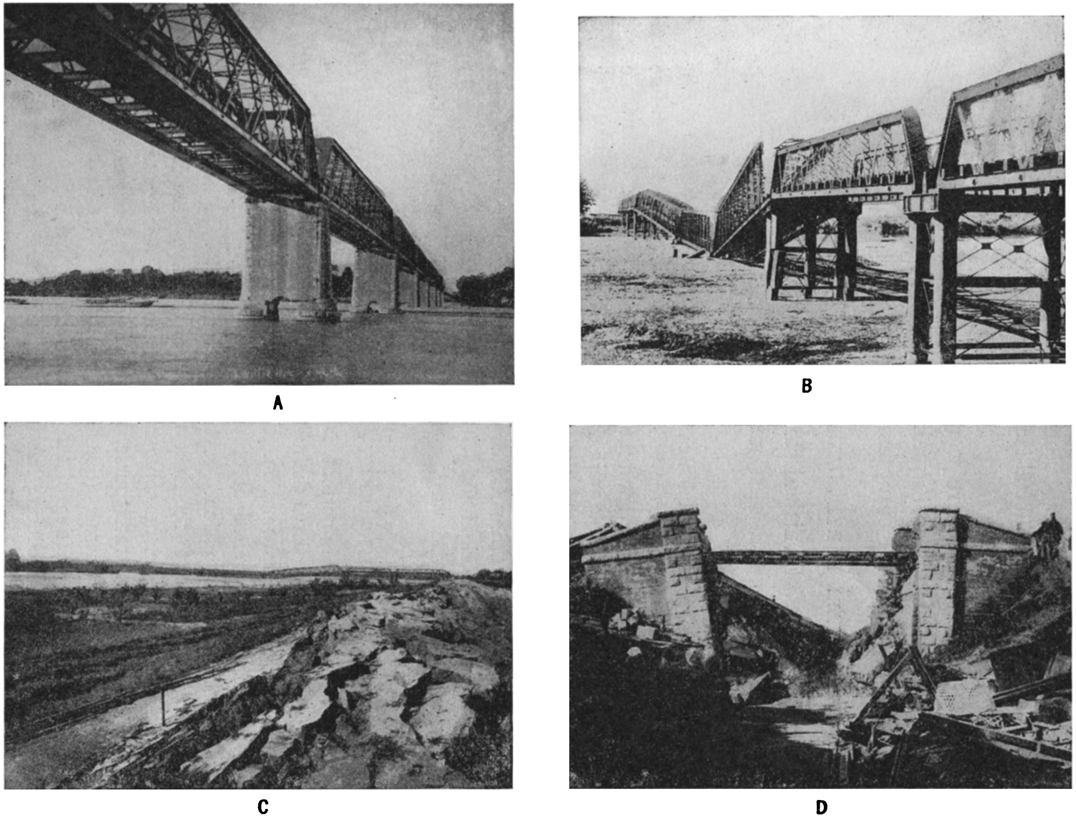

FIG. 3.—Damage sustained by bridges during the Japanese earthquake of 1891 (after Milne and Burton). (*A*) Kisogawa Railway bridge with fractured piers. (*B*) Nagaragawa Railway bridge fallen in part into the river bed but still continuous. (*C*) Nagaragawa bridge (in distance) with fissured river banks in foreground. (*D*) Biwajima Railway bridge showing distorted abutments and fallen arch.

Speaking of a bridge near the Kiso River and also near the great Kisogawa bridge just referred to, the authors state that this bridge consists of two spans of 70-foot plate girders, and add:

> The end walls or abutments are cut through horizontally, and the solid brick "well" which supported the central pier between the spans is broken across like a stick. The upper portion of the well has moved three feet sideways on the line of fracture.
>
> From the photograph it will be seen that while the south abutment is broken through horizontally, the side walls are cracked diagonally.
>
> At the end of the crack where it rises from the ground it was discovered, on taking the brick work down for reconstruction that the earthquake had thrown the foundations of each wing wall 10 inches away from the well formation of the abutment which originally was touching the foundations. (See Fig. 5, *A*.)

Thus in this case, also, it appears that the abutments showed evidences of the shortening of the distance between them in their tilting back from the river.

Probably the most interesting and instructive example yet furnished of the deformation of bridges during earthquakes is that of the railway bridge over the Nagara River (See Fig. 3, *B* and *C*).

> The main part of the bridge consists of five independent thrust girders of wide span. The piers at the two ends of one of these girders are completely wrecked and the girders have fallen bodily into the bed of the river. The piers on either side of the two mentioned are partly wrecked, and the girders between them and the first-mentioned girders rest, each with one end in the river bed, the other on the top of the partly destroyed pier. The remaining girders are in their original positions or nearly so.
>
> It will again be observed that the portion of the bridge which has fallen relative to the part which remains standing, has been thrown some distance out of a straight line.
>
> Examination has shown that this displacement is not simply a displacement of the upper-work of the bridge, but the ground with the screw-pile foundations has been shifted a distance of several feet up the stream.
>
> The embanked approach to the Nagaragawa bridge has been thrown into a regular series of undulations of such extent that, looking along the line eastward from the eastern abutment, the appearance is almost that of looking along a switch-back railway.

It will not fail of observation that the bridge spans, though fallen in some instances from their foundations, and further shifted some distance up stream, approximate to curved sections, in both horizontal and vertical planes, yet maintain their continuity across the river

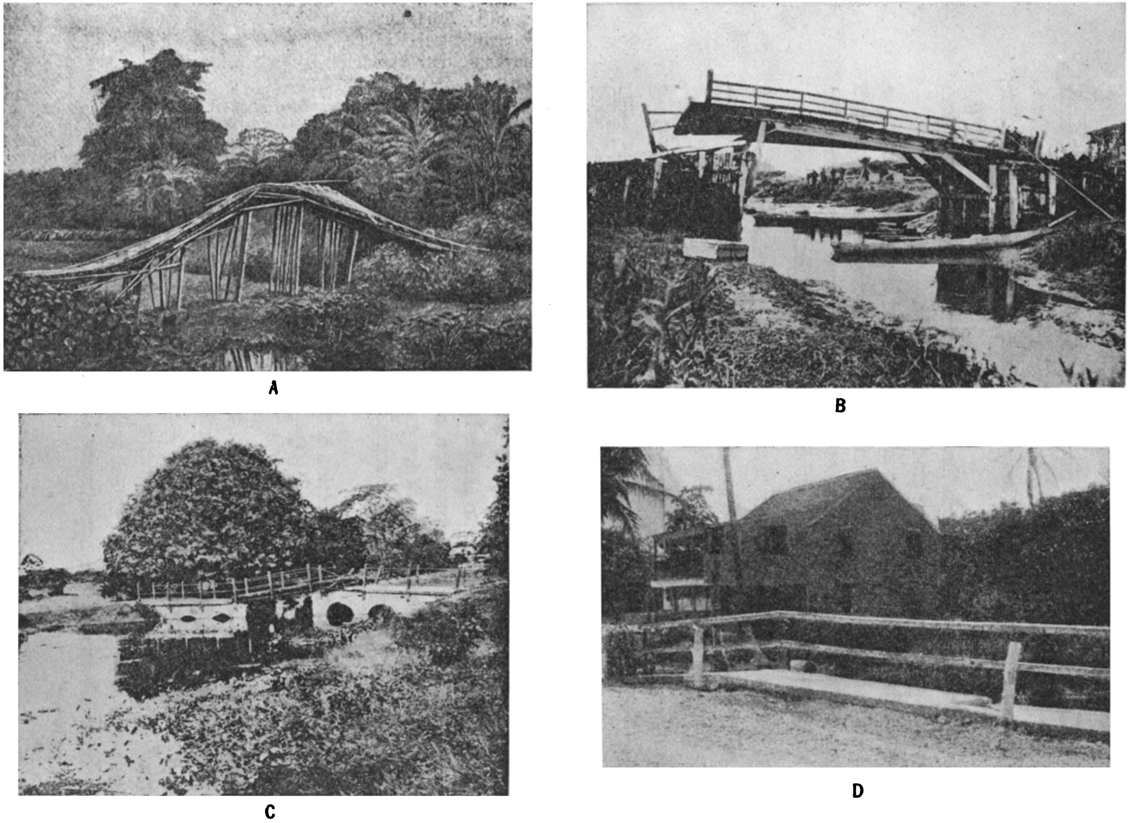

FIG. 4.—(*A*) Bridge over a stream at Rangpur after the Assam earthquake of 1897. The center of the stream channel has been raised (after R. D. Oldham). (*B*) A rustic bridge after the Schonai (Japan) earthquake of 1894, with its girder pushed up over the abutment (after Kikuchi). (*C*) Bridge over a canal at Rangpur after the Assam earthquake of 1897. Girder pushed up over abutment (after R. D. Oldham). (*D*) Bridge near Kingston damaged by approach of abutments during the Jamaica earthquake of 1907 (after Fuller).

from bank to bank. The narrowing of the distance between banks which is thus indicated is considerable. This is shown in Fig. 3, *B* and *C*.

### EARTHQUAKE OF SCHONAI, JAPAN, IN 1894

An interesting illustration of the approach of the abutments of a rustic bridge during the Schonai earthquake is seen in Fig. 4, *B*. In this case the girder has slid up over one of the abutments so as to allow the latter to move toward the stream.[1]

### GREAT ASSAM EARTHQUAKE OF JUNE 12, 1897[2]

Next to the Mino-Owari earthquake this great disturbance has furnished perhaps the largest number of examples of wrecked bridges. These will be discussed, therefore, in some detail:

Bridge on Grand Trunk Railroad west of Gauhati:

> At the western end of the Gauhati Bazar is a bridge of three girders carrying the Grand Trunk Road over a small stream, which here joins the Brahmaputra. The original length of the bridge, as measured along the hand rail, was 99 feet, 4 inches, while the present length, between the same points, is 97 feet, 10 inches. The bridge has therefore been shortened 18 inches. This has been caused by fissuring of the banks on both sides of the stream, the abutments having been carried forward. One of the piers has been tilted over probably by the thrust of the girder. There are no cracks in the abutments. (P. 266.)

Assam Bengal Railway (Reported by T. D. Latouche):

> I went out along this line as far as the bridge over the Kapili River about forty-one miles from Gauhati. The rock cuttings, in gneiss, have not been affected in the slightest degree by the shock, but where the line passes over alluvium, the embankment has settled down, carrying the rails with it. Many of the culverts are badly cracked, apparently from the same cause as has affected the bridge mentioned above at Gauhati, viz., the fissuring of the banks of the streams and the consequent sliding forward of the abutments and wing walls. The piers of the large bridge over the Kapili are cracked through horizontally at about 2 feet above the ground level, and the girders have shifted lengthwise on top of the piers. (P. 267.)

Bridge over the Bara Khal (Reported by G. E. Grimes):

> In the case of the bridge over the Bara Khal the piers have fallen right over into the river and disappeared entirely; before the earthquake this bridge had

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[1] D. Kikuchi, *Recent Seismological Investigations in Japan*, Pub. E. I. C., No. 19 (Tokyo), 1904, Fig. 46.

[2] R. D. Oldham, *Mem. Geol. Surv. India*, Vol. XXIX, (1899).

eleven piers standing, each with 9000 cubic feet of masonry, there being three spans of sixty feet and six spans of forty feet, but after the shock only two piers on each bank were left standing and the intermediate space is quite blank. At the time of the shock the two embankments are said by those who were present to have moved toward one another and then apart, when the telegraph wires were snapped across and some of the insulators were hurled violently for a considerable distance backward from the river. (P. 295.)

The damage to the bridges on the Assam Bengal Railway is thus summarized by Mr. Grimes:

The abutment walls are cracked or broken and have come to, shortening the span. . . . This coming-to of the abutment walls is often quite considerable, and in spans of twenty feet it is sometimes as much as a foot. Accompanying this movement we, in almost every case, see that on one or both sides of the bridge the embankment has sunk several feet. When the bridges have wing walls to the abutment, this forward movement has cracked and considerably damaged them, but where, as in the case of many of the smaller bridges, there are straight return walls, the pressure has acted along the length of the walls and not across them, and so the bridges have mostly escaped with little or no damage. The coming to of the abutments and consequent shortening of the span has either resulted in the buckling up of the girders in the center, or the girders have pushed back on and broken off the balance walls of the abutments. In a few cases the piers of the bridges have been tilted over to the side, but in most cases only inwards. (P. 296.)

Gauhati Road Bridge over Umkra River:

The large bridge on the Gauhati Road about one and one-half miles from Shillong, over the Umkra River, has suffered severely. The abutment on the southeast side fell entirely, carrying the girders with it. The two piers and the abutment on the northwest side, which are of more recent construction, remained standing, though somewhat cracked. (P. 271.)

Bridge near Shampur on Kuch Bihar Railway:

Near Shampur, also, the hexagonal brick piers of one of the bridges have been broken through horizontally and the upper portion has shifted slightly: this form of fracture appears to have been rather common, and though at first supposed to be of no great moment, was subsequently found to render the bridges unsafe for either rapid or heavy traffic. (P. 284.)

Bamboo bridges over canal (reported by H. H. Hayden):

The canal being, as already stated, a line of weakness, it is not surprising to find that the banks on each side are cut up by fissures, while its bed has risen in some cases through several feet, the central portion being now above the water: this is well shown by the bamboo bridges which have been shot up in the center (see Fig. 4, *A*). The same effect is seen in numerous places between Rangpur and Kuch Bihar, where bridges of small span cross canals or swamps. If the bridge has a central pier then the pier has been shot up and the bridge broken. This is, however, in some cases due partly to a sinking of the abutments as well. (P. 285.)

### Manshai Bridge:

In the neighborhood of Dewan Hat, however, the line has suffered severely, and the bridges, particularly that over the Manshai River, have been broken (see Fig. 5, *D*). At about seven miles south of Kuch Bihar, a small bridge passing over a water channel in swampy land has been damaged by the thrusting-up of the central pier. (P. 287.)

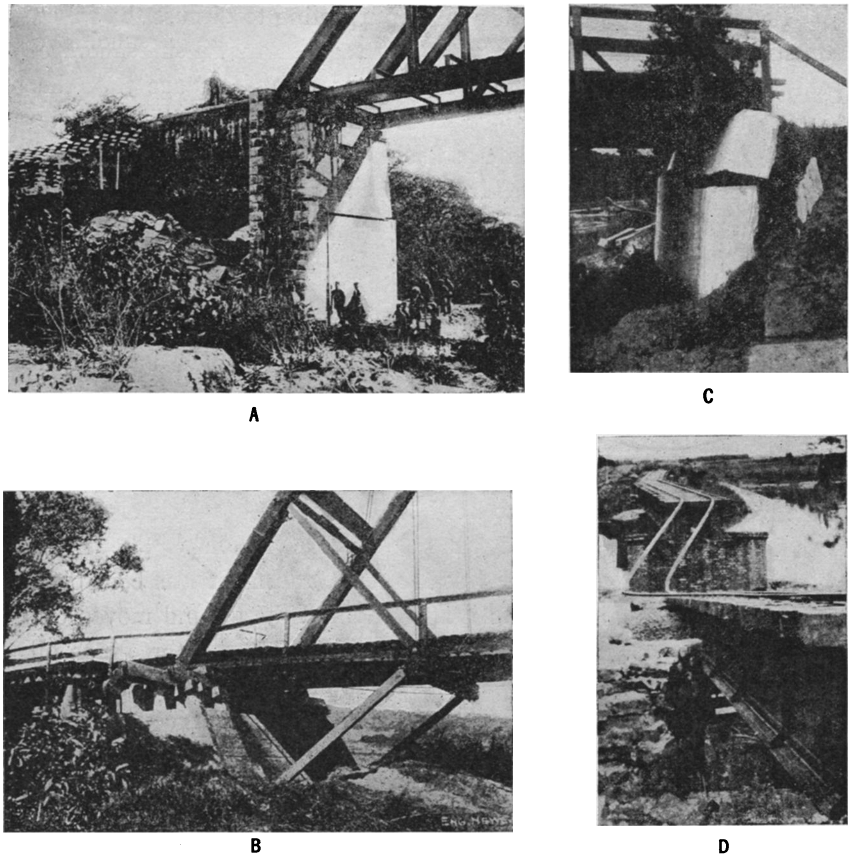

FIG. 5.—(*A*) Bridge of Tokaido Railway near the Kisogawa with abutment broken by the approach of river banks during Japan earthquake of 1891 (after Milne and Burton). (*B*) Bridge over Salinas River with distorted abutment damaged during California earthquake of 1906 (after Derleth). (*C*) County bridge over Pajaro River at Chittenden, California, after the California earthquake of 1906 (after Dudley). (*D*) Manshai bridge after the Assam earthquake of 1897 (after Oldham).

Examination of the photograph of the Manshai bridge reproduced in Fig. 5, *D*, will show in the lateral kink of the rails and the dropping of the span conformity with the general rule that there is a shortening of the distance between piers.

## CALIFORNIA EARTHQUAKE OF APRIL 18, 1906

The report upon this earthquake[1] purporting to discuss the effect on structures particularly is a disappointment in that a single bridge only is mentioned, and this in such ambiguous language that the nature of the damage sustained can only be guessed.[2] The bridge referred to is that of the Southern Pacific Railway where it crosses the Pajaro River near Chittenden Station. Abundant material for a study of the damage to bridges existed, and we are fortunate in having been able to collect the data concerning some interesting examples. One of these is illustrated by a photograph of the county bridge over the Pajaro River at Chittenden, which, as well as any we have seen, illustrates a typical effect of earthquakes upon such structures (see Fig. 5, *C*).[3]

The damage sustained by the Salinas Highway Bridge in the same province has been described and photographed by Derleth[4] (see Fig. 5, *B*), and is shown to conform to the rule which elsewhere obtains. The bridge rests on pile-bent abutments. The north abutment was not disturbed, but the south abutment was bent back from the river at the top and it is stated that the ground moved out toward the river beneath it a distance of six feet. A three-inch oil pipe-line crossing the bridge was bent into an *S* and ruptured.

In the same article Derleth has given us a clear account of the damage to the Southern Pacific Railway bridge over the Pajaro River, from which it appears that this case is an unique exception to the general rule. The bridge lies across the rift line of California at a very acute angle and it is probable that the large shiftings on this line have here played an important rôle in producing the damage.[1] The pulling of the girder out of its seat on the south abutment apparently indicates a widening of the distance between banks during the earthquake, and this would appear to show that the shear on the rift plane is here in a contrary sense to that which has generally obtained at other places.

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[1] Grove Carl Gilbert, Richard Lewis Humphrey, John Stephen Sewell, and Frank Soulé, *The San Francisco Earthquake and Fire of April 18, 1906, and Their Effect on Structures and Structural Material*, Bull. 324, U. S. Geol. Surv., 1907, pp. 170, pls. 56.

[2] *Loc. cit.*, p. 20, Pl. XI *A*.

[3] Reproduced in Salisbury's *Physiography* (New York, Holt & Co., 1907), p. 424.

[4] Charles Derleth, Jr., C. E., "The Destructive Effect of the San Francisco Earthquake of 1906," *Engineering News*, Vol. LV, No. 26 (June 28, 1906), p. 712, Figs. 15 and 16.

Through inquiry of the engineering department of the Southern Pacific Railway Company it was found that in addition to the Pajaro bridge above mentioned slight damage was sustained in other sections of the road. Some few trestles were thrown out of line and "two small drawbridges were affected slightly by the movement of the landing piers toward the center piers—just enough in each case to bind the bridge."[2] On the Atchison, Topeka and Santa Fe Railway there was a Bascule bridge in which the two leaves approached each other so closely, as a result of the disturbance, that the bridge was rendered inoperative until changes were made. This gradual approach of the two abutments has continued in the absence of sensible shocks during the succeeding two years.[3]

In the report of the subcommittee on railway structures to the General Committee of the American Society of Civil Engineers[4] it is stated that embankments crossing marshy ground generally sank (sometimes as much as eleven feet), and that trestles in soft material moved or were thrown down. Railway drawbridges across little creeks and inlets about the Bay of San Francisco "were affected by a slight movement of their piers, in many cases resulting in the bridge binding so that it could not be opened until some repairs were made." On the California and Northwestern Railway the bridge at Bohemia and the one over the Russian River at Healdsburg were both slightly shifted on their piers at one end. At Duncan's Mills on the North Shore Railroad a combination span a hundred and twenty feet long "had the eye-bars in the lower chord buckled by movement of the abutments toward each other" (see Fig. 6, *B*).[1]

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[1] *Loc. cit.*, p. 711.

[2] Letter from J. H. Wallace, Assistant Chief Engineer, Southern Pacific Company.

[3] Letter from H. C. Phillips, Chief Engineer, A. T. and S. F. Ry. Co.

[4] "The Effects of the San Francisco Earthquake of April 18, 1906, on Engineering Constructions," Report of a general committee and six special committees of the San Francisco Association of Members of the American Society of Civil Engineers (with discussions by twenty-three others, Ed.), *Trans. Am. Soc. Civ. Eng.*, Vol. LIX, (December, 1907), pp. 208–329.

The sub-committee appointed to investigate highway structures in lieu of a report offered the statement that such structures had been singularly immune from damage. This meager statement is curiously contradicted by the evidence furnished in the printed discussions. The highway bridge across a creek tributary to Tomales Bay near Port Reyes Station, which had eight panels or sections, had its north abutment sink two to three feet and approach the south abutment so much that in reconstruction the north end panel was not used but was in part replaced by an apron (see Fig. 6, *C*).[2] At Watsonville was a bridge which according to Derleth was distorted in the same manner as the Salinas bridge above described and with which it is compared.[3] In each case the deformation was ascribed to "differential surface movement distinct from elastic vibration."

Two additional instances have been mentioned in the report with illustrations by Galloway,[4] to wit: the Alder Creek bridge north of Point Arena in Mendocino County, the other the Gualala bridge south of the same point. The first mentioned (Fig. 6, *D*) now lies on the bed of the stream across the rift line, the other, a steel structure, had one end of the girder dropped twenty-eight feet. These bridges were not examined by the engineers, and the views afford the only evidence at hand.

### KINGSTON EARTHQUAKE OF JANUARY 14, 1907

A very recent example which illustrates the usual deformation of a bridge at the time of a destructive earthquake, has been furnished

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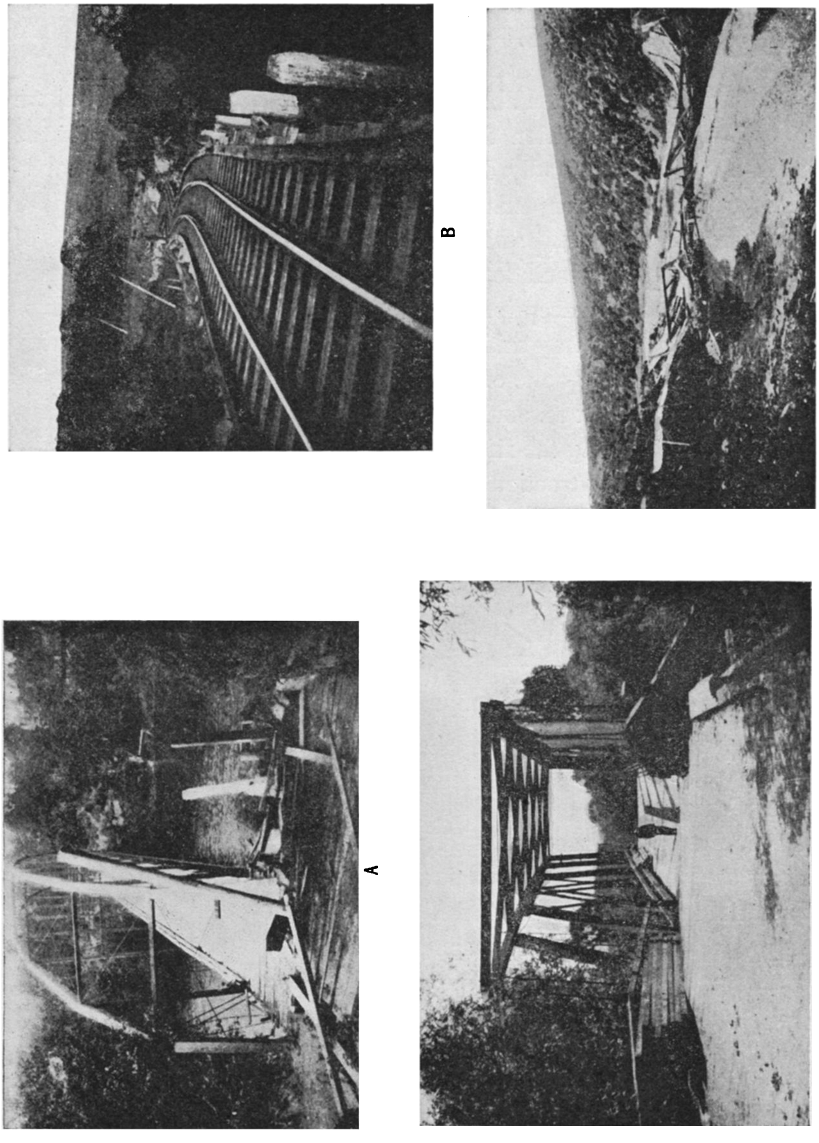
[1] J. H. Wallace, H. C. Phillips, R. M. Drake, and E. M. Boggs, sub-committee, *loc. cit.* p. 259, Pl. 53, Fig. 1.

[2] H. H. Wadsworth, *M. Am. Soc.*, *loc. cit.*, p. 270.

[3] Charles Derleth, *loc. cit.*, pp. 311–15.

[4] John D. Galloway, *M. Am. Soc. C. E.*, *loc. cit.*, Pls. 57, 58. From a personal letter from Mr. Galloway it is learned that Alder Creek enters the ocean some twenty miles north of Point Arena. The Gualala River is a mountain stream which enters the ocean about the same distance south of Point Arena. The Gualala bridge, which was built some ten years ago, gave trouble from the fact that the ground beneath the piers showed a tendency to slide so that it was necessary to put the bridge up upon a false work and realign the piers.



A

B

C

D

Fig 6

by Fuller's account of the Jamaican earthquake of January 14, 1907.[1] A cement culvert at the mouth of a stream was buckled up and broken through the movement of its walls toward the center of the valley (see Fig. 4, *D*).

It is believed that the above data are sufficiently full and decisive to warrant the conclusion that during a destructive earthquake the banks of valleys generally draw together so as to shorten the intervening distance. The examples of deformed bridges which have been offered in evidence, have not been selected for the purpose of proving a point, but include all which have come to the writer's attention. The unique exception to the law which otherwise controls, is furnished by the railway bridge over the Pajaro River damaged during the California earthquake of 1906; and, inasmuch as this bridge lies across the rift line at an acute angle it seems likely that special shearing movements along the rift plane have here been of larger measure than the normal contraction of the valley.

It appears, further, to be a fact of general observation, that a fissure or series of parallel fissures open during earthquakes along the banks of rivers parallel to their courses (see Fig. 3, *C*). According to Milne[2] within the Aichi prefecture in Japan, after the earthquake of 1891, more than four hundred miles of river banks, water trenches, and roads were found destroyed through action of this kind. On river banks the fissured zone and hummocky ground looked as though gigantic plows had torn out furrows several feet in width and sometimes as much as twenty feet in depth, and this character of the surface extended from ten to fifty yards from the river. Such structures can be only in part explained through the shaking down of loose material such as is found in a railway embankment on which the tracks approach bridges, for the reason that such mere removal of support to rails should give the effect of tension rather than compression.

Thomas Oldham, who first seriously studied the fissured river banks in connection with the Cachar (Indian) earthquake of January 10, 1869,[3] went out from the conception of an earthquake centrum explained the cracks as due to earth waves, and assumed that a single crack, if one only was formed, opened just a half-wave-length back from the river's edge on either side.

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[1] M. L. Fuller, "Notes on the Jamaica Earthquake," *Jour. Geol.*, Vol. XV, 1907, pp. 718, 719.

[2] John Milne, *Seismology*, p. 148.

[3] *Quart. Jour. Geol. Soc. Lond.*, Vol. XXVIII (1872), p. 255. See also *Mem. Geol. Surv. India*, Vol. XIX, Pt. 1, pp. 52–56, Pl. vi.

When we take into account the observed effect of the earth movements upon bridges, it is clear that something quite different from the mere passage of an earth wave must be invoked in order to explain these geological changes. Not only is the space between valley walls in part closed up, but for a considerable distance back from the banks the bridge approaches show the effect of compression (see especially Fig. 1, *A*). The piers of the bridge which rest upon the stream bed also suffer changes not explainable, upon Oldham's theory (see Fig. 3, *A* and *B*). Whether occupied by streams or not (see Fig. 3, *D*) it seems to be clear that the vicinity of valleys is marked by unusual surface compression in a direction at right angles to the valleys.

It is perhaps unnecessary to here bring forward the evidence obtained from observations of a different kind that local compression of the ground actually occurs during earthquakes. On the one hand, there are the continuous stone curbings and buried metal pipes which are found buckled up from the surface of the ground; and on the other, there are the many variations in the longitudinal shear along fault lines which must be accounted for either through differential contraction, expansion, or both.[1] On the Baishiko fault opened in Formosa on March 17, 1906, a change in the direction of the longitudinal shear between two stations less than three-fourths of a mile apart, indicated a change in linear distance between the two points before equally distant of about fourteen feet.[2]

That the changes of superficies to which we have called attention are wholly restricted to the mantle of unconsolidated rock material is most improbable; though, as we shall see, there is reason for supposing that it is locally much larger within the mantle than within the underlying rock. To account for an extension of surface of any portion of the consolidated outer shell of the lithosphere, it is only necessary to assume a very slight increase of each of the joint spaces present within the rock. A contraction of the surface area may, perhaps, likewise be best explained through a change, and here a reduction in width, of individual joint spaces. To this change may be added the effect of some actual compression of the unfractured portions of the shell. In Fig. 7 let *A* represent in its lower portion a section of the outermost consolidated shell of the lithosphere, and in its upper portion the mantle of unconsolidated deposits in which the valleys have been cut. As the compression of the shell reduces the width of the joint spaces and otherwise diminishes the superficies of the shell, its envelop of loose material by reason of its lack of

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[1] For examples see the author's *Earthquakes*, pp. 62, 66, 73–75, 228–31.

[2] Omori, *Bull. E. I. C.*, Vol. I, No. 2, Pl. xvii.

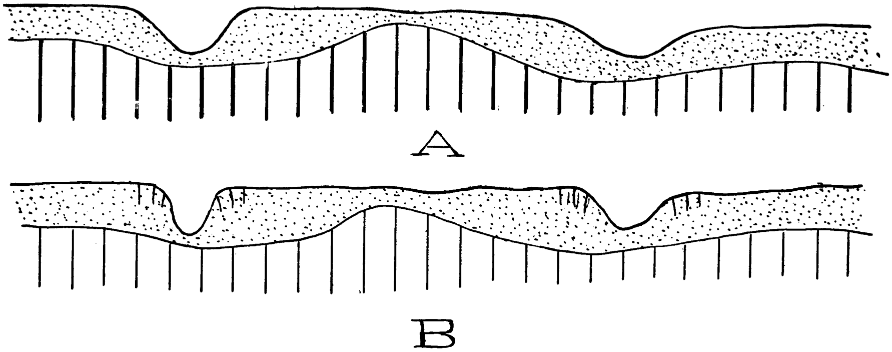

FIG. 7.—Diagram to illustrate the narrowing of valleys during earthquakes as a result of crustal contraction, (*A*) before contraction; (*B*) after contraction.

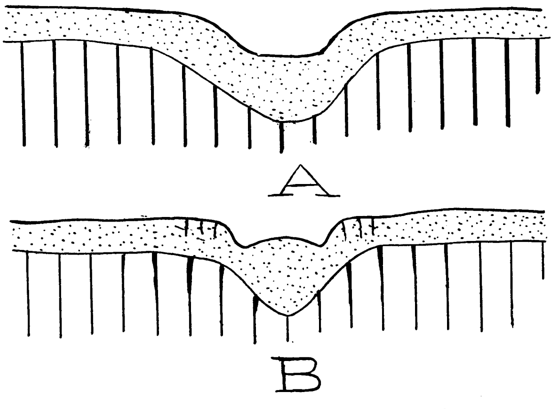

FIG. 8.—Diagram to illustrate the pushing up of the beds of rivers during earthquakes as a consequence of crustal contraction, (*A*) before contraction; (*B*) after contraction.

rigidity is incompetent to transmit the same stresses, and hence tends to remain in *status quo*. In the mantle a slip over the basement floor of rock will take the place of a more uniformly distributed adjustment within the floor. The valleys which intersect the mantle, must, in consequence, reveal an amount of crustal contraction far in excess of the average for the district (see Fig. 7, *B*).

Wherever rock valleys interrupt the surface of the shell beneath a newer valley in the mantle of loose soil (see Fig. 8, *A*), that portion of the shell which lies outside the level of the bottom of the rock valley, will by reason of the breaks in its continuity be less capable of transmitting the compressive stresses. This may otherwise be expressed by saying that this outer layer is not fully included in the pinch to which the layer immediately below it is subjected. A consequent reduction of its competency to transmit the earth's stresses will be greatest for the immediate vicinity of the valleys, and hence the joints will there be closed by a portion only of the average amount. The walls of the rock valley must therefore tend to approach with the result that they will push up the center of the river bed into a definite ridge, and further give the effect of a settlement at the banks where abutments are placed (see Fig. 8, *B*). Next to the narrowing of the distance between banks and the accompanying parallel fissuring, these changes are, as we have seen, the ones most frequently observed along rivers after a destructive earthquake.

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